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EXPLORATION PRINCIPLES FOR MAJOR ENGINEERING WORKS

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SOIL MECHANICS AND FOUNDATIONS DIVISION

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EXPLORATION PRINCIPLES FOR MAJOR ENGINEERING WORKS

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SYNOPSIS

This paper presents guiding principles for the formulation of exploration programs for various engineering structures. The powerplant section discusses various design factors which affect the development of geologic investigations for this type of structure. Similarly, basic principles for developing exploration programs for canals, water tunnels, and earth and concrete dams are discussed. The limitations of publication space make it necessary to treat what is a very broad subject in a very concise manner. For example, suggestions only can be given as to the types of subsurface investigation methods to use and no attempt is made to present the multitude of such methods available. Powerplant exploration is discussed in somewhat more detail than any of the other structures because the author has found a noticeable lack of information on this subject in the literature.

INTRODUCTION

The principles discussed herein are a generalization of methods that the engineering geologist, in combination with the designing engineer, can use in developing exploration programs. These principles are only basic and, therefore, have to be expanded according to the characteristics of each individual design and according to the geologic conditions found at the structure site. Exploration standards vary considerably according to the engineering firm or designing agency. However, those enumerated herein have been developed over a period of years in exploring all types of engineering structures (many of them are now in use by the Bureau of Reclamation) and thus, it is hoped, may serve as a pattern for future standardization.

Power and Pumping Plants

Design Factors Involved

It seldom is desirable to predetermine a definite pattern of exploration holes for these types of structures; experience has shown that numerous changes are made prior to the final design and construction of the plant, and the explorations must be modified to suit these changes.

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For example, the number and size of the units may be changed, thus altering the dimensions of the plant; hydraulic model studies may show that a shift in alinement of the tailrace channel will result in more favorable hydraulic characteristics; the penstock location might be altered; or it may be decided, as a result of preliminary explorations, to realine the plant to take advantage of better electrical leads to the switchyard.

When cost studies are made, an economic balance must be achieved between the length of the penstock and the length of the tailrace channel; i.e., due to adverse foundation conditions, it may prove more economical to move the plant out and away from the hill and thus lengthen the penstock with a subsequent shortening of the tailrace. On the other hand, such cost studies may prove it cheaper to move the plant into the hill, design the footings to accommodate for the adverse conditions, and then lengthen the tailrace channel.

Damage to the generators or penstock connections may take place if even minor differential settlements occur. This fact must be kept in mind when planning and analyzing the results of an investigation program for a powerplant. Other matters to be taken into consideration are the possible utilization of piling or caissons. Is the ground water or soil of such a chemical quality that it would seriously corrode steel piles? Are large boulders likely to interfere with driving, or are they likely to be mistaken for bedrock and thus chosen as a foundation for a caisson or the piles?

The character of the material that will be excavated should be determined as it may be necessary to place the powerplant and tailrace channel in a deep cut. It would then become necessary to determine safe angles of repose for the cut slopes, the erosive qualities of the material, the necessity for lining the tailrace, and the water table location. The latter determination will facilitate proper drainage of the backfill around the plant and the tailrace slopes and give a preview of construction difficulties with water.

Reconnaissance Stage

The first stage of investigation includes the preparation of a surface geologic map, or at least a surface reconnaissance by the geologist preparing the drilling program. During or after the completion of the surface examination, two or three (depending on geologic conditions) drill holes in the general powerplant area will locate bedrock and the quality of the various layers in the bedrock. As accurate design data may not be available at this stage of the investigation, it may not be possible to locate the holes at the bearing walls or the center line of the units. A rule of thumb for determining the depth of these initial holes is: The depth of the hole should be equivalent to one and one-half times the longest width of the powerplant (e.g., if the plant is to be 50 feet wide, then the hole should be 75 feet in depth below the base). If bedrock is not encountered, the designer may request that the holes go to a sufficient depth to encounter bedrock, providing that in the geologist's judgment bedrock is at a reasonable depth. Additional drilling may be required at this stage to locate a better (from a foundation standpoint) powerplant site. The drill program shown in Figure 1 was designed to locate the

best possible foundation for Flatiron Powerplant on the Colorado-Big Thompson Project of the Bureau of Reclamation. Holes DH 1, 50-3, -5, and -15 through -19 were drilled in an attempt to locate firm bearing material. It was then found that geologic subsurface conditions were so erratic (Figure 1A) that the topography and the most economical penstock location should control the final powerplant location. Subsequently, the remainder of the holes indicated on Figure 1 were drilled to clearly ascertain the foundation material under the plant and the pump discharge lines (DH 50-20 and -28).

The size of the reconnaissance holes should be at least Nx (Nx core is $2\frac{1}{8}$ inches in diameter) in order that some data can be obtained on the jointing and the fracture systems of the bedrock. Holes of even larger diameter are desirable in severely fractured or jointed rock. These initial holes may be supplemented at later stages of the reconnaissance investigation by such additional exploration as may be necessary to clarify the geologic picture.

Design Stage

When the lay-out of the powerplant is more definitely established, it is economical to proceed further with the exploration. If the final grade of the plant is known, the holes should penetrate 50 to 100 feet below that final grade, depending upon the type of load to be applied by the bearing walls and the generator units. Customarily, in this final program, holes are drilled at the corners and one hole in the center of the plant. If the plant is of considerable size and the foundation conditions warrant it, additional holes may be drilled under the center line of each unit, under heavy bearing walls, and in the tailrace area. If the geology is complex and unusual structural conditions such as faults are encountered, sufficient additional holes should be drilled to correlate these structural anomalies with the design of the plant.

Another criterion for guiding the explorations is that it is advisable, whenever possible, to place the entire powerplant on one type of rock. For example, if you encountered a series of schists and pegmatites, it would be advisable to delineate the pegmatite areas to permit placement of the powerplant thereon, since there is greater possibility for differential settlement if the plant rests on two types of bedrock, each of which may have different moduli of compression. Also, limiting the foundation to one type of bearing material may reduce the complexity of footing designs.

In cases where the beds are lenticular, and soft and hard layers interfinger, it may not be economically feasible to determine the extent of all of the soft layers prior to excavation. In such cases, it is only necessary to drill sufficiently to determine <u>that</u> they exist and <u>are</u> irregular. When they are exposed in final excavation, the soft materials can be excavated and replaced with lean concrete ("dental work"). Throughout the floor of the final excavation, and prior to the afore-mentioned "dental work," shallow holes should be put down to assure that a competent member is present at a reasonable excavating depth beneath the soft materials. Jackhammer holes can be used to identify foundation materials during the final excavation stages, providing the geologic character of

the rock is already well known. The geologist can observe the jackhammer in operation and study the color of the rock dust blown out of the hole, and the ease of jackhammer penetration. He then can determine with some accuracy which of the previously known strata are being penetrated. Jackhammer exploration was done at Flatiron Powerplant (Figure 1A), as the soft silty and shaly sandstones of the Fountain formation formed irregular layers and lenses that could not be located prior to construction without a costly number of drill holes. After excavation, jackhammer holes disclosed the extent of the soft layers and they were removed and replaced with lean concrete.

Sampling

Considerable care is always required during sampling operations. All bearing materials must be determined as during the drilling it is easy to overlook or wash away fault gouge, a clay bed, a bentonite streak, or a soft sandstone layer. Usually, when soft materials are encountered, it is best to proceed with penetration spoon-type or small-diameter drive sampling rather than core drilling. For hard rock, core drilling is adequate although it may have to be supplemented by later penetration or drive sampling if soft layers are encountered within or beneath hard seams.

If it is not possible to use drilling equipment due to difficulty of access, test pits may suffice for small plants. However, such pits are limited to above the water table and to soft materials. Test pits are not economical if they go below the water table and excessive pumping is required, if loose running sands are encountered, or if it becomes necessary to excavate in hard rock requiring considerable blasting. In such instances, it may be necessary to bring in portable core drills.

The type of sample to be recovered for testing depends on the type of material encountered. In soft materials, it is advisable to recover 4- or 6-inch-diameter "undisturbed"[2] samples. This size is adequate for consolidation and triaxial shear tests in the laboratory. Such sampling should not be done until a spoon-type penetration test has determined the types of materials present and which of these would require laboratory testing. This procedure reduces the number of costly large-diameter holes that otherwise might be required. From the hard rock smaller samples often suffice, as unconfined compression or triaxial shear tests can be run on 1½ -inch-diameter rock samples.

All undisturbed samples for laboratory testing should be carefully handled to minimize disturbance, and in the winter months should be thoroughly protected against freezing during shipment to the laboratories.

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2. The term "undisturbed" when applied to samples obtained by various drilling or driving methods is merely relative, as some degree of disturbance commonly occurs regardless of the sampling device used. Even if the individual particles appear to remain in their original positions after the sample is retrieved, the earth pressures originally acting on the particles when in the earth are relieved and thus the fabric of the sample undergoes some degree of alteration—either slight or large depending upon the type of material.

All samples should be sealed with cheesecloth and paraffin to prevent loss of moisture.

Unconsolidated Foundations

Usually a large powerplant will not be placed on an unconsolidated foundation if it is possible to reach firm bedrock materials within economical limits. Such firm materials may have to be reached by piles, caissons, or pier footings. Therefore, it will be necessary to ascertain the nature of the unconsolidated materials to determine the proper type of foundation design: (1) What type of pile will have the best driving and bearing characteristics; or, (2) is it more feasible to sink a caisson or excavate for a pier-type footing? Wherever piling is contemplated, it is advisable to drive test piling; the driving difficulties can thus be surmised, and a rough idea of the bearing characteristics obtained from load tests on the test piles. After application of test loads, a determination can be made as to the length of pile that will be required, the bearing capacity, and thus the number of piles that will be required for the foundation.

Supplementary Considerations

1. The character of the materials that will be exposed in the tailrace channel. Will they be capable of withstanding water action, or will they require concrete lining or riprap? For example, some basalts, although quite hard, are so badly fractured that high velocities in the tailrace result in a plucking action and gradual or rapid erosion. At what slopes can they be excavated and still remain stable? Will their stability be endangered by the velocity or saturation of the water in the tailrace?
2. Ground-water action. Will the foundation materials immediately below the plant be adversely affected by changes in ground-water conditions due to plant operation? Will backwater from the tailrace result in leaching of the foundation material, or will consolidation occur due to the water action, such as that which occurs in some aeolian deposits?
3. Switchyards usually require foundation investigation. In these structures, an estimate must be made of the differential settlement in order to select the type of switchyard design. In the strain-type bus structure, the busses are constructed of suspended cables and thus some settlement can be tolerated between individual structures. In the rigid-type yard, the busses are in rigid pipes and thus any settlement between structures would damage the bus connections. The latter type of structure is usually the more economical, however, and will be used if foundation conditions justify it. In some cases it may even be economical to remove soft materials to ensure a satisfactory foundation. The ultimate design can thus protect against severe differential settlements which would break bus bar connections.
4. In transmission line towers, sudden, high heel or toe pressures can be expected due to wind, ice loads and/or sudden breakage in the lines. This sudden impact of differential pressure may cause the soil to fail by shear rather than by consolidation. These types of

failures, therefore, provide the clues to the type of field sampling and laboratory testing required. The engineering geologic studies have to consider that transmission line tower foundations are designed against pull-out—both sudden and gradual, as well as differential settlement.

5. The possibility of earthquake action is considered in the design of powerplants. The frequency, duration, intensity, and epicenters of such quakes often can be determined by geologic bibliographic studies. Considerable data on earthquakes are available in the literature of the United States Coast and Geodetic Survey and the United States Geological Survey.

6. The depth of the frost line and the possibility of permafrost should be considered. Frost can affect the nature of the foundation materials sufficiently to cause erroneous interpretations of the drilling results. The presence of permafrost will necessitate special design considerations.

7. Slaking. Sometimes, materials are encountered in the foundation that are subject to deterioration ("slacking" or "slaking") by the air once they are exposed. Such excavations can be protected by the application of sealers such as asphalt emulsion or gunite. The existence of such critical materials should be determined during the exploration to protect against construction difficulties from excessive slaking and also to prevent deterioration of the foundation material under the completed structure. In Figure 2, the freshly exposed siltstone surfaces at Granby Pumping Plant are being coated with a special asphalt emulsion to prevent their deterioration before concrete placement. When such coatings are used, special design consideration is given to their effect on the coefficient of friction between the base slab and the foundation material.

8. Vibration. In unconsolidated materials such as loose sands, it should be determined if the vibration of the powerplant will cause them to consolidate. In hard rocks the designer may require information on whether the rock is acceptable to the placement of dowels. Such dowels can act either as anchors or as agents that will change the vibration frequencies and thus protect the plant against destruction by harmonic vibrations impressed by the equipment.

9. Rock falls and snowslides. Very often, hydroelectric plants are placed at the bottom of steep declivities that may have overhanging and loose rocks. In such circumstances, the possibility of serious rock falls should be carefully investigated. Such falls have occurred in the past, causing serious damage to the powerplant and penstocks. Protection may be achieved by scaling the loose rocks (provided it is possible to remove all of them), by placing the plant underground, by heavily reinforcing the roof, by erecting deflector walls in the gulleys to direct the rocks away from the plant proper, or by a combination of these measures. Sometimes loose rock slabs can be anchored by the roof-bolt procedures now being used in tunnel construction. At Kortes Dam in Wyoming, the granite massif exhibited intense jointing with resulting loose blocks. Scaling operations could not economically remove all such loose material. Thus rock stabilizer walls (Figure 3) were erected to anchor the extremely large loose slabs,

and rock deflector walls were built on both abutments to prevent smaller rocks, loosened by weathering, from hitting the powerplant. In addition, the plant roof was heavily reinforced to protect against occasional rocks that would bypass the deflector walls.

The possibility of avalanches should be investigated, as steep declivities often are prone to snowslides. Such slide conditions also can result from the construction of the penstocks. Clearing operations may remove a heavy timber growth that in the past has been acting as a deterrent to slides. Thus, an excellent slide path is developed which funnels snow into the powerplant. The force of such slides can be great enough to move the plant from its foundations as well as to completely bury it. It usually is best to relocate the plant to protect it against slides, excavate the penstocks underground to prevent excessive clearing on the surface, or some attempt can be made to construct artificial barriers or deflectors. Many Swiss installations and villages have been protected by such devices, although in some instances they have built their powerplants underground to achieve complete protection.2/

Underground Powerplants

The exploration for underground powerplants should include surface geologic mapping and a combination of tunnels and surface and subsurface drill holes. Evaluation of the joint, fracture, and fault systems are of the utmost importance in determining the economies of underground construction. Decisions will have to be reached as to the amount of roof support, the type and quantity of wall support, and the design provisions necessary for moisture and water control. An evaluation of these factors can best be attained by geologic studies of a tunnel (or drift) into the actual plant location. This drift can also be utilized as a base for subsurface drilling to locate or determine the extent of faults, shear zones, etc. At some underground plants, the exploratory drifts were so located that they later could be used as an access or ventilation tunnel for the completed powerplant. Some assistance in evaluating rock conditions can be obtained by studying the available literature on underground plants in Switzerland, Italy, Norway, and Sweden.2/ 3/ 4/ 5/

Canals

The design considerations in the development of exploration programs for canals are: (1) settlement, (2) stability, and (3) permeability.

Reconnaissance Stage

In the initial stage of the investigation, it is advisable to prepare a reconnaissance surface geologic map of the canal line. Such a map should encompass all outcrops within about 100 feet (more or less, dependent upon the size of the canal and the depth of cut that will be necessary) of the proposed final excavation lines of the canal. Contacts between different formations, between formations and overburden, and between overburden types (e.g., a contact between valley fill and loessial deposits) should be carefully noted. These data are all necessary to the

accurate classification of the excavation for specifications and to provide information on the possibility of seepage and of slides.

Subsurface Exploration

The extent of the subsurface exploration program depends upon the size of the canal, the location of canal structures, and the complexity of the geology. For main canals, drill holes at 1,000-foot intervals along the center line of the canal usually are sufficient. However, at any point on the line where there is doubt as to the subsurface geology, a hole should be put down to determine the nature of subsurface materials. An example of such a program is given in Figure 4, wherein the depth of the overburden and the character of materials within the canal prism were investigated.

Additional holes should be drilled at all major structure locations, such as siphons, checks, siphonic spillways, major bridges, and railroad or other canal or river crossings.

In all drill holes it usually is necessary only to drill 10 feet below the bedrock surface if the rock is found at or above the canal invert grade. If bedrock is at considerable depth below the invert, then it is necessary to drill the hole only 10 feet below grade. However, materials (such as loess) may be encountered that are subject to rapid consolidation or destruction under water action. In such cases, the holes should penetrate the critical material to any underlying permeable strata, or to the water table, regardless of the thickness of the critical material. For example, the entire thickness of a loess deposit can settle under the action of water, regardless of the amount of load placed on it. This type of deep hole, however, is pertinent only to canal structures. Usually the determination of the thickness of such critical materials is not necessary elsewhere on the canal line, as unusual settlement probably only would cause repairable minor damage.

From the logs of the drill holes at 1,000-foot intervals along the canal, it can be determined whether additional holes will be necessary to further study the permeability and settlement characteristics of the canal materials.

Tests. It is difficult to run quantitative permeability tests in a drill hole in unconsolidated materials. The Bureau of Reclamation has adopted the practice of performing field perpeability tests along the canal line, using a constant head permeameter (Figure 5).6/ In bedrock, open end or pressure permeability tests give good qualitative results and fair quantitative estimates of the permeability.7/ Settlement and stability characteristics can be determined with some accuracy from laboratory tests on undisturbed samples of the critical materials. Field penetration testing is of some assistance to these studies, but requires correlation with laboratory tests for accurate interpretation.

Supplementary Considerations

1. Slides. Possible potential slide areas within, or up or downhill from, the canal prism should be considered in canal exploration. Existing landslides should be carefully mapped to determine if they will be disturbed by the canal excavation or by saturation.

2. Frost action. The possibility of frost action should be investigated. Will the materials penetrated by the canal be subject to frost action? The investigation should disclose: (1) the location of, and possible vertical fluctuations in the ground water; (2) the capillarity of the foundation materials; (3) the depth of frost penetration; and (4) service records of local structures.

3. Expansive soils. Another condition that should be investigated is the possibility of expansive soils in the subgrade materials. Expansive-type clays when contacted by canal waters may swell sufficiently to disrupt the canal lining or seriously disturb major canal structures.

4. Drains. Where a canal penetrates hard rock, an estimate should be made on the permeability of such rock; that is, can or does ground water flow through structurally developed fissures in the rock? Thus, a decision can be made as to whether it will be necessary to place drains along the canal. If the ground-water flow is restricted due to the tightness of the natural rock openings, the geologist can assist in determining the most strategic location for drains that will reduce frost action and uplift on the lining.

Water Tunnels

Although the criteria mentioned hereafter are specifically intended for water tunnels, many of them are applicable to all types of transportation tunnels. The basic considerations for planning exploration programs for tunnels are:

1. Determination of type and amount of support
2. Possibility and quantity of water flow
3. Possibility of gas
4. The estimation of underground temperatures
5. The possibility of rock bursts or bumping ground
6. The possibility of surface blowouts as a result of leaks in the lining

In some cases it is necessary to determine if the rock can safely accept all or part of the stresses imposed by the internal hydrostatic head in the tunnel; or if the rock is competent enough to withstand sudden increases in the external hydrostatic and rock pressures on the lining as a result of the sudden emptying of water from a pressure tunnel. These determinations are required in the design of and the necessity for reinforcement in the lining. (The need for lining itself depends not only upon rock conditions, but also upon the effect the absence of lining will have on the hydraulic properties of the tunnel.)

Reconnaissance Stage

In this initial investigation stage, a detailed surface geologic map should be prepared. The location, dip, strike, and extent of all formations, faults, joints, and other structural features should be shown. Rock types and contacts between formations should be carefully mapped for a sufficient distance on both sides of the tunnel line to permit their projection on cross sections to the grade of the tunnel (Figure 6).

Design Stage

Upon the completion of the surface studies, it is possible to locate exploration holes to the best advantage to further clarify the subsurface geologic picture. If the tunnel is not at too great a depth below the surface, it may be possible to drill holes along the tunnel line at sufficient intervals to accurately depict the stratigraphy. A study of the cores will assist in estimating the support that may be required, as well as disclosing the possibility of excessive water flows and gas. If the tunnel is to be driven at a great depth below the surface, it often is not economically feasible to drill holes to tunnel grade, particularly at those points where the tunnel grade is several hundred or several thousand feet below the surface. Instead, the interpretation of conditions at tunnel grade will have to be obtained from surface geology or from drill holes along the line that are just deep enough to penetrate the overburden and thus disclose the underlying rock types. It is advisable to drill the portal locations to determine the stability of the materials that will be exposed during the initial excavation. During the actual driving of the tunnel, it often is desirable to drill pilot holes ahead of the main heading to determine the possibility of high-water flows, extremely soft ground, or the effectiveness of grout; thus, adequate precautions can be taken by the contractor before the trouble actually is encountered.

Support Estimates

There are no established rules for accurately estimating the amount of support (Figure 7) that will be required in the tunnel. The estimates have to be based upon actual experience with a number of tunnels in various rock types. Usually, the surface geology and the drill cores will indicate whether extremes of support, such as liner plate, will be required, or whether supports may be eliminated entirely from some sections of the tunnel. Research now is being carried on to determine the relationship between the type and number of supports and rock types.[3]

Construction Stage

The geologist should be present during the tunnel excavation to accurately log the tunnel (Figure 8). Such logs are of inestimable value if difficulties occur during the operation and maintenance of the tunnel. Also, such logs are of great assistance to research on establishing definite relationships between the geological conditions and the type of support used.

The geologist also can assist the contractor in locating supports to the best advantage. For example, the geologist often can predict the presence of slabby materials which, although at first glance do not appear to require support, will later come crashing down into the tunnel.

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3. The Committee on Engineering Geology of the A.S.C.E. has a task committee on the "Influence of Geological Factors on Tunnel Construction" which now is engaged in studying the relation of tunnel supports to geology.

Earth Dams

Consideration during the exploration for earth dams should be given to: (1) the bearing quality of the foundation; (2) permeability characteristics; (3) possibility of slides on the abutments; (4) the permeability of the reservoir; (5) the adaptability of foundation materials to grouting; (6) the presence of geologic anomalies, such as crushed zones which may require overexcavation; (7) the adverse effects of reservoir water on the foundation materials, such as piping, consolidation, or leaching; and (8) the location of embankment materials.

Reconnaissance

A surface geologic map should be made to assist in the location of drill holes and to locate unusual features which may not be readily apparent at first glance, such as large faults or buried channels. Aerial photographs of the dam and reservoir areas are very helpful in the preparation of such maps. In fact, the map often can be prepared directly on an enlarged air-photo.

The stratigraphy of the abutments should be determined. Dips and strikes of the formation are necessary to the analysis of landslide possibilities; and to the determination of ground water conditions. For example, high permeability and adverse dips and strikes of the beds in the abutments may prove that the ground water is a tributary from the main stream, and thus the reservoir may not hold water.

In the reconnaissance stage, three drill holes usually are sufficient to depict roughly the geologic conditions along the dam site. One hole is placed in the thalweg[4] of the valley and one hole on each abutment of the dam. From the picture thus developed, further exploration is formulated.

Design Stage

Once the stratigraphic picture is delineated, drilling can be initiated:

1. To obtain samples for laboratory testing to determine the engineering properties of the foundation materials (See "Sampling" under "Power and Pumping Plants");
2. For permeability tests to provide a qualitative analysis of the seepage characteristics of the foundation (Satisfactory quantitative tests are difficult to obtain);
3. To locate clays, bentonite seams, or other materials, that would decrease the coefficient of friction under the final structure; also, such soft plastic materials can inhibit grouting to such an extent as to make it entirely infeasible;
4. And, if the previous studies indicate grouting is required, to show if the foundation materials can be cement-grouted, or are readily adaptable to bituminous, chemical, or clay grout.

The exploration can be supplemented by trenches into the abutments. Such excavations provide a great deal of information at a low cost as

4. The thalweg is the line following the lowest part of a valley.

they may be easily dug by a bulldozer or dragline. Similarly, "drifts" or tunnels into the abutments may be necessary to detailed geologic studies. These types of excavations may disclose unconformities between the formations that were not noted in the drill holes. Only from such trenches and drifts can the degree and character of jointing and fracturing in the bedrock be correctly ascertained. Test pits also can be utilized for similar information. It may be necessary to dig trenches or test pits in order to obtain adequate undisturbed samples for subsequent laboratory testing. Figure 9 illustrates a complete exploration program for an earth dam, including holes on the cut-off trench and on the appurtenant structures.

The depth and character of the channel fill should be carefully determined by drilling. This information will determine the necessity for well points during construction of the cut-off trench, the extent and depth of the cut-off trench, and the advisability of using the excavated materials in the embankment. The holes should be accurately logged and permeability tests run to determine the efficiency of a well point installation.

Foundation Studies of Appurtenant Structures

Once the afore-mentioned investigations are completed, exploration should proceed for the appurtenant structures to the dam, such as the outlet and spillway works. Closely spaced holes along the exact location of the structures are necessary to determine accurately the depth to which concrete walls and slabs should be placed to insure a minimum amount of settlement. If the design is not far enough advanced to establish the final structure locations, an efficient method of conducting such exploration is to lay it out on a grid system with drill holes at the intersections of grid lines. Such intersections may vary from 100 to 1,000 feet apart depending upon the complexity of the foundation materials and the structure size (see drill program for spillway on Figure 9). The results from such drilling often are used (1) to classify the "required" excavation for later use in the dam, and (2) to ensure that the design of the spillway encompasses adequate safety factors against sliding.

Additional drilling that may be required in connection with an earth dam is that necessary for highway or railroad relocations. In such investigations, the foundations of major structures such as overpasses or bridges should be explored.

Construction Materials Exploration

A major consideration in exploring for earth dams is the development and location of borrow and riprap areas. The borrow areas usually are located as close as possible to the structure. Due to the relatively small amount necessary, the riprap areas can be at some distance from the dam.

Preliminary to drilling, airphoto studies and the preparation of a geologic map of the surficial materials will permit the economical location of borrow area drill holes. As can be seen in Figure 10 the most promising borrow areas usually can be selected before actual drilling starts. A few reconnaissance holes, usually with an auger, will give a rough idea

of the zoning and type of material. It then is best to continue the drilling on a grid system so that information from the holes can be readily used in zoning the borrow area for placement in the dam. Such holes are usually drilled with a power or hand auger and often are shallow, rarely exceeding 20 or 30 feet or the depth of the ordinary shovel cut. Borrow areas for the impervious materials needed in the dam should be located above the water table. The pervious materials can be obtained below the water table, although at considerably greater cost; however, it is often found that the only pervious materials are those within the stream bottom proper. Sack ("undisturbed") samples for laboratory tests are often sufficient for determining embankment characteristics.

Concrete Dams

Perhaps the most important criterion for the development of a program for a concrete dam is that such a structure, unlike an earth dam, requires a sound rock foundation. However, some types of concrete dams, such as "slab and buttress" or Ambursen, can be designed for weak foundations, if there is a scarcity of earth materials for an earth dam.

The initial phases of the exploration are similar regardless of the type of ultimate design. However, the development of the final stages of the investigation should be guided by whether the structure is an arch, gravity-arch, gravity, or slab and buttress dam.

Reconnaissance Stage

The procedures during this stage of exploration are similar to those used for earth dams. Usually a surface geologic map is prepared and a hole is drilled in each abutment and in the river section to locate and determine the nature of bedrock. In the mapping, considerable emphasis has to be placed on the accurate plotting of joint and fracture systems. If an arch dam is contemplated, the magnitude and direction of the systems can have considerable influence on the thrust characteristics of the completed structure. A reconnaissance is made of the reservoir basin to locate any possible sources of leakage. Also, at this stage, the concrete aggregate sources should be located. The proximity of such deposits can greatly influence the selection of the dam type; e.g., if aggregates are relatively scarce, it may be more economical to design a dam that uses a minimum amount of concrete, such as "thin" arch or a slab and buttress. On the other hand, the proximity of large quantities of aggregate will permit the design of the type of structure that is most suitable for the topography and geology of the site.

Possible leakage through abutments or under the dam must be very carefully investigated. A concrete dam may impound water under considerable head; thus formations that normally are tight under low head can become a dangerous source of seepage and uplift under a high head.

Another problem that may develop is the erroneous interpretation of solid rock on the abutments. It is not unusual for an extremely large mass of rock which has slipped from the hillside above to be mistaken for an integral part of the main rock massif. Such a situation could, of

course, be disastrous if a high thrust were put upon it from a structure such as an arch dam, or from direct water pressures from the reservoir.

Design Stage

Usually there is little time separation between the completion of the initial drilling and the design drilling. The problems disclosed by initial reconnaissance drilling may lead immediately into an additional drilling program. And, usually, it is more economical to continue the drilling while the rigs are still on the site than to move them back at a later date. This particularly true of exploration for concrete dams, as the topography suitable for such structures may be very rugged and thus result in difficult and costly set-ups for the drill rigs.

At this stage it becomes necessary to learn more about the nature of the jointing and fracture systems. This information can best be obtained from exploratory tunnels or "drifts." These drifts need be no more than man size—4 by 6 feet—and, although expensive, the information obtained from them usually results in the elimination of several drill holes. The photograph in Figure 11, the heading of an exploratory drift at Swan Lake Dam site in Alaska, illustrates the jointing and fracturing details that can be secured in such drifts. Careful logs (Figure 12) as well as photographs should be prepared for later record and design information. Abutments should be thoroughly explored by both drilling and drifts, and it may be desirable to excavate shallow trenches to determine the depth of weathering and thus the depth of stripping that will be required.

In estimating stripping quantities, the geologist should keep two criteria in mind: (1) the depth of weathered material that it is necessary to remove to obtain a sound foundation; and (2) the amount of rock that will normally have to be removed to shape the canyon for the dam. In the case of shallow weathering, the acceptance of the latter criterion may <u>automatically</u> result in the elimination of all weathered material.

As the geologist is the one who usually becomes the most familiar with the natural characteristics of the site, it may fall on his shoulders to determine the accuracy of available topography. Accurate topography is absolutely essential when an arch dam design is contemplated. Inaccuracies in the topographic map may result in the omission of gullies intersecting the abutments at such a position that the thrust of the arch would "daylight."

During this stage of drilling, it usually becomes necessary to drill holes along the canyon bottom to a depth in the rock equivalent to the height of the dam. Such deep holes are required to determine the possible existence of soft layers that could be affected by the weight of the structure. Such holes usually are drilled not only along the axis of the dam, but also along the up and downstream toes. For high dams, however, the designer may be satisfied with shallower holes and geologic extrapolation to greater depths.

As with any engineering structure, geologic anomalies may exist in the foundation that will require considerable drilling and tunneling to fully explore; e.g., it may be necessary to trace out a fault intersecting the axis; the width of the zone affected by the faulting; and estimate the

amount of disturbed material that should be removed and replaced with concrete ("dental work"). Angle holes are usually valuable at this stage as they can be drilled at an angle that is normal (or perpendicular) to the "anomaly," thus, the full width of the questionable geologic feature can be explored. A complete exploration program for a gravity dam, including drifts, vertical and angle holes, and test pits is given in Figure 13.

Exploration for Appurtenant Structures

Usually the normal drilling program for the dam will overlap the sites of the appurtenant structures for the dam, such as the diversion tunnel, the outlet works, and the spillway. However, if the spillway is located in a topographic saddle some distance from the main dam, it will be necessary to explore the foundation of this structure to determine the permeability and bearing characteristics of the foundation.

If the diversion tunnel is of considerable length, it will be necessary to extend the drilling program to include a sufficient number of holes along the center line of the tunnel to demonstrate any possible construction difficulties. Such an extension is done only when the results of surface geology are not sufficiently conclusive to satisfy both the geologist and the design engineer.

Exploration for appurtenant powerhouse structures would follow the same criteria as given in the earlier paragraphs entitled "Power and Pumping Plants." Explorations for any appurtenant long tunnels would be the same as those given in the paragraphs entitled "Tunnels."

Diversion Dams

In comparison with the structures previously discussed, diversion dams usually are minor in size and may be constructed of either earth or concrete. If they impound only a low head of water and the structure is relatively small, detailed drilling will not be warranted unless foundation conditions are particularly critical. In fact, some of these structures may be "floated" on underlying soft materials. The foundation should be investigated, however, in sufficient detail to advise the designer of any possibility for differential settlement and uplift.

CONCLUSIONS

As stated in the introduction, this paper has not attempted to describe in great detail exploration programs for major structures. It rather has attempted to establish principles by which the average geologist untrained in engineering geology can intelligently and safely develop exploration programs for such structures. For example, many omissions have been made such as the use of large-diameter holes commonly called calyx holes, selection of drilling bits and drill rigs, geophysical surveys of bedrock and materials sources, and many others, the use of which the geologist will acquire by his constant associations with engineering geology. He very often will find that the driller on the job may be a good "practical" geologist and thus able to assist him a great deal during the course of the investigation.

This discussion also is directed at the engineer, in order to better acquaint him with the work of the engineering geologist. Many of the principles enumerated herein can also be translated to types of structures not discussed. For example, as far a geological foundation analysis is concerned, and neglecting vibration effects, there is some similarity between a powerhouse and a large office building.

ACKNOWLEDGMENTS

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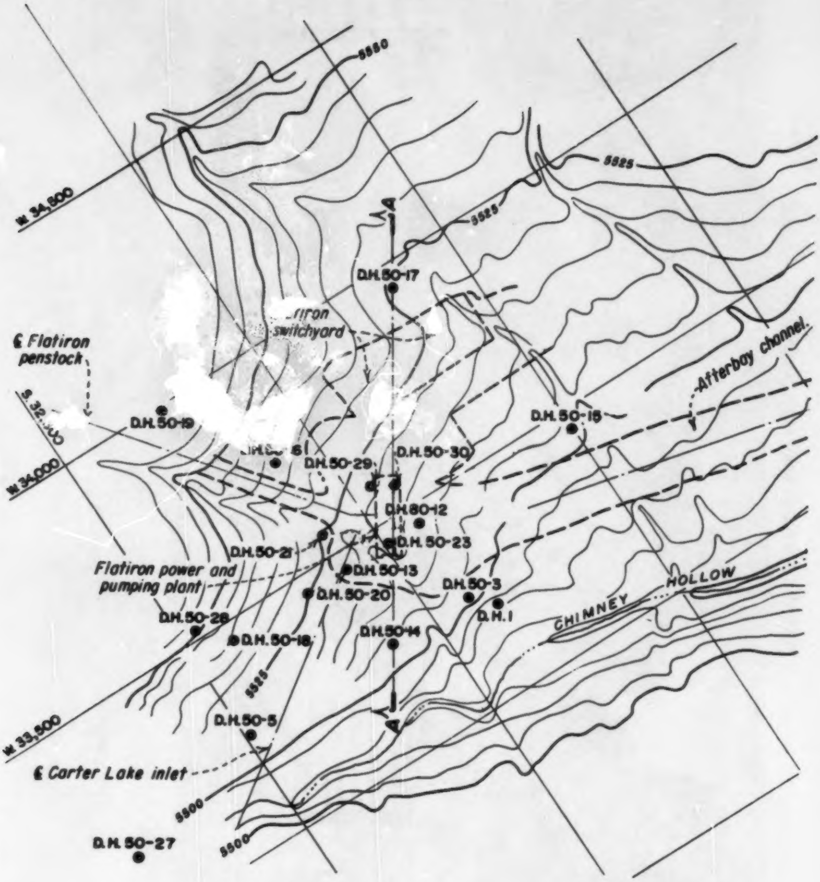
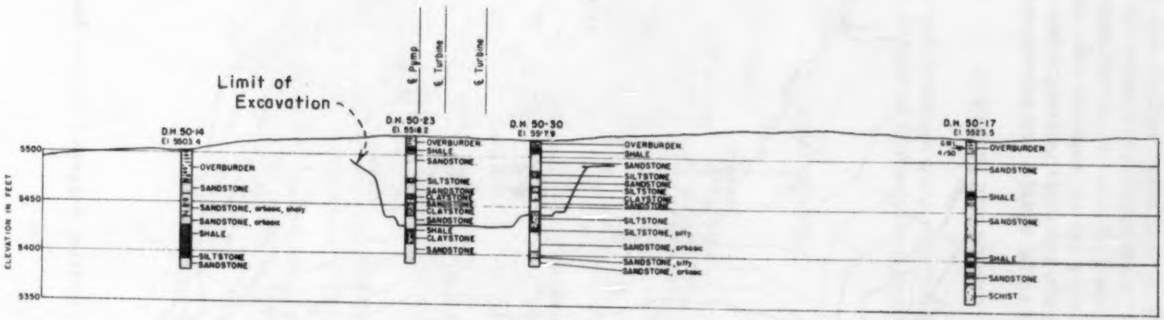


FIG. I. Expl[illegible]on Program (Flatiron Power Plant)



SECTION A-A

FIG. 1A. Cross-Section (Flatiron Power Plant)

FIG. 2. Placing Asphalt Protective coating

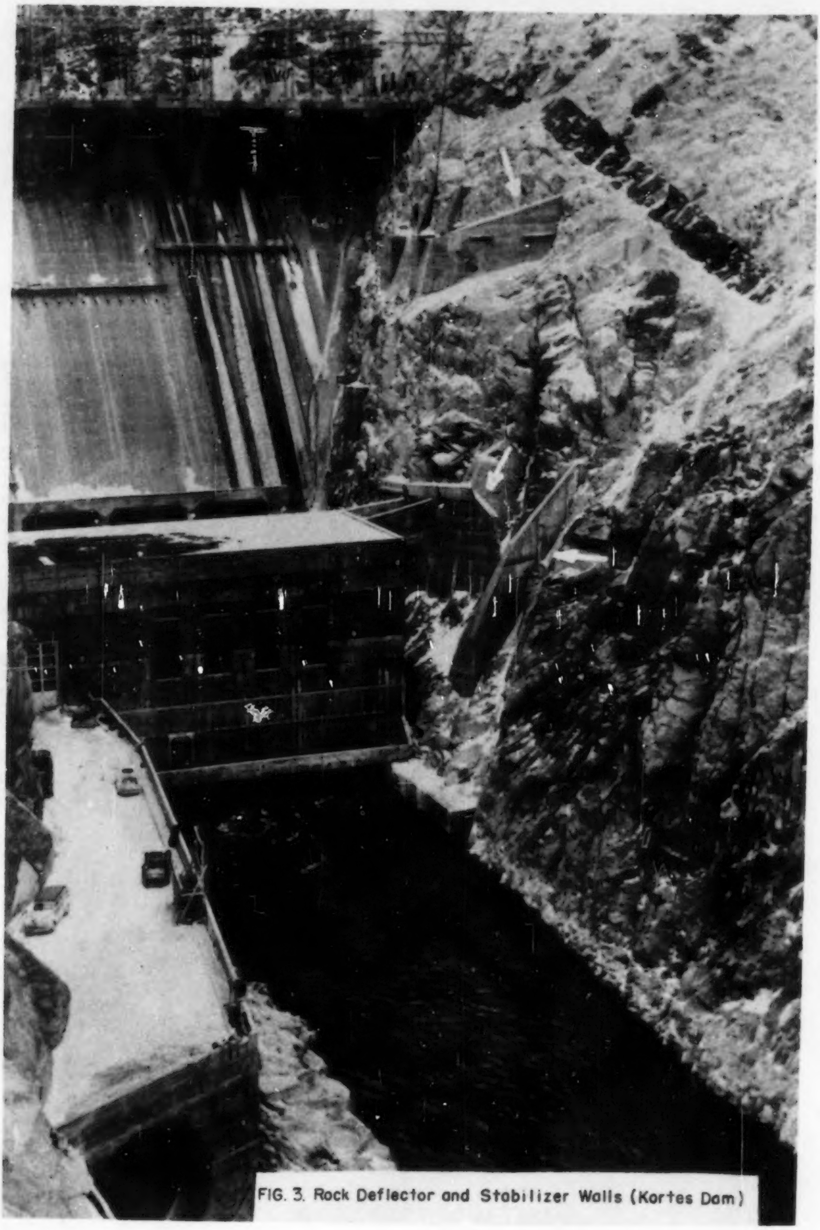


FIG. 3. Rock Deflector and Stabilizer Walls (Kortes Dam)

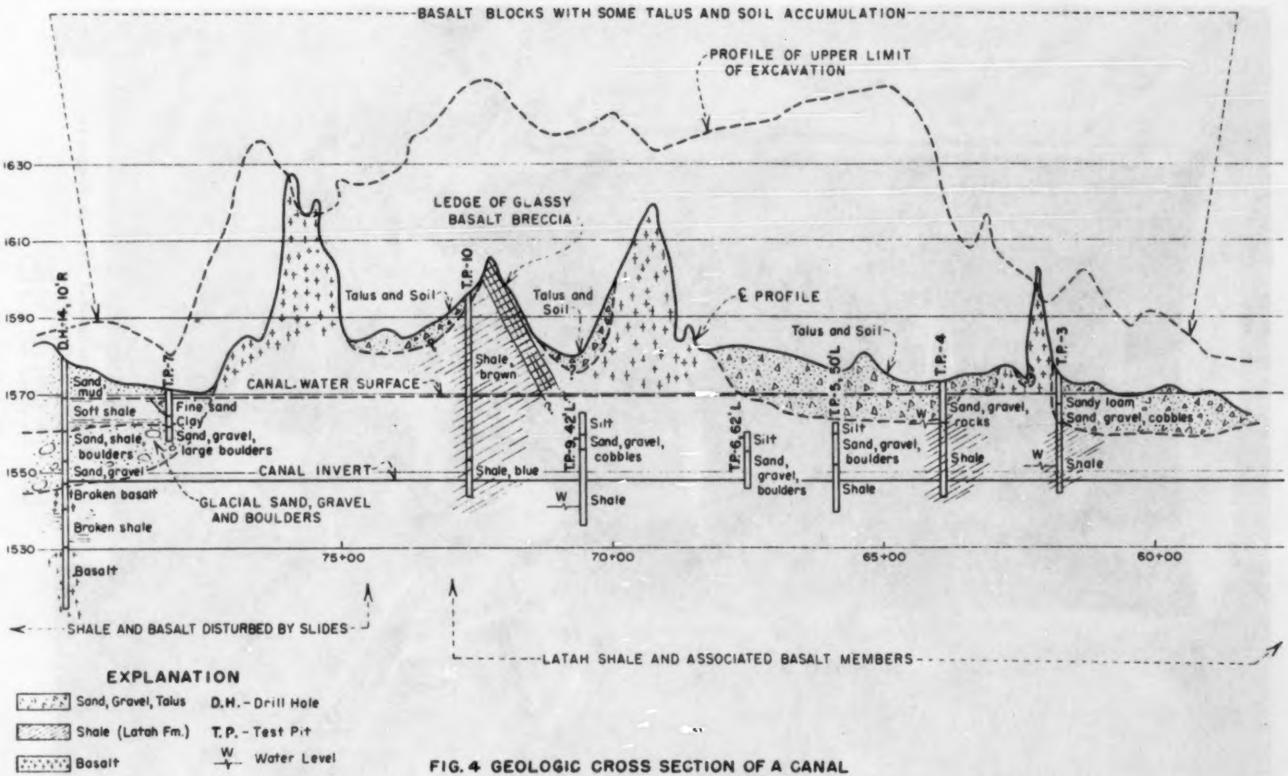


FIG. 4 GEOLOGIC CROSS SECTION OF A CANAL
Grand Coulee Feeder Canal, Washington

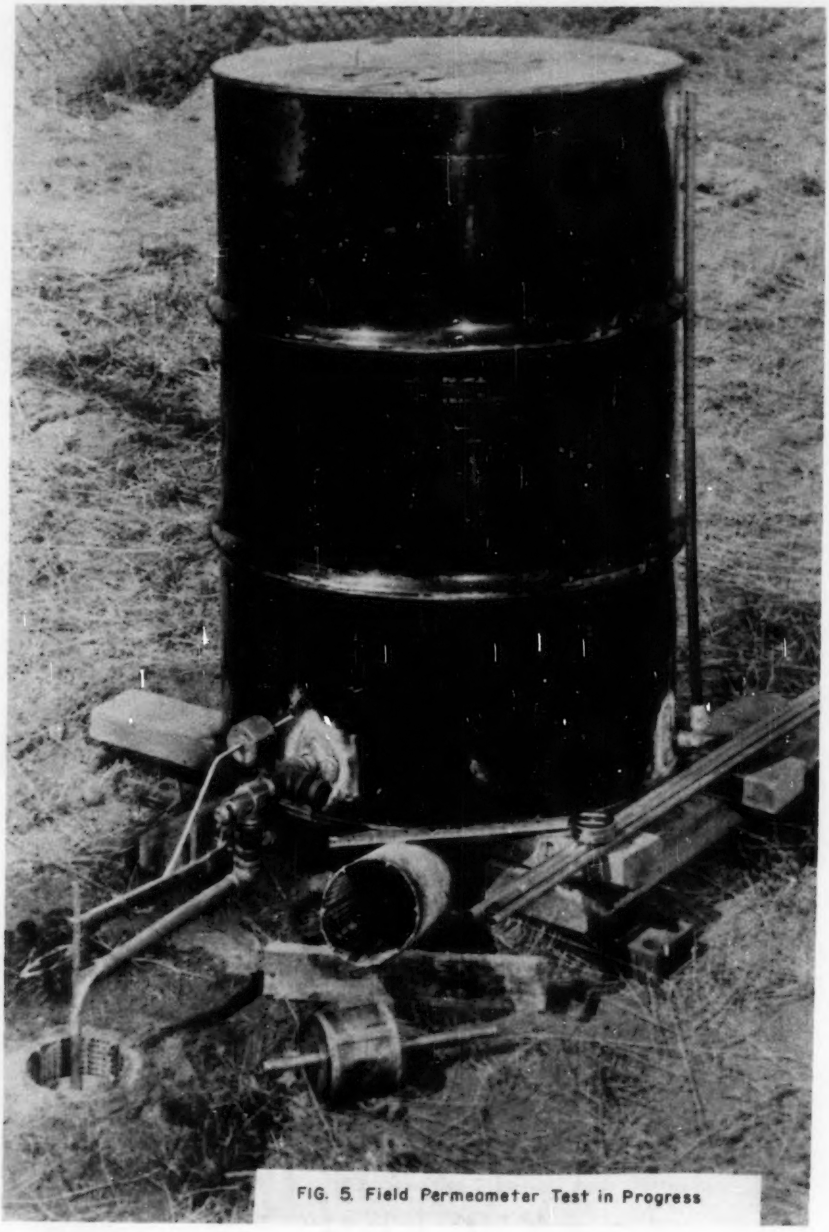
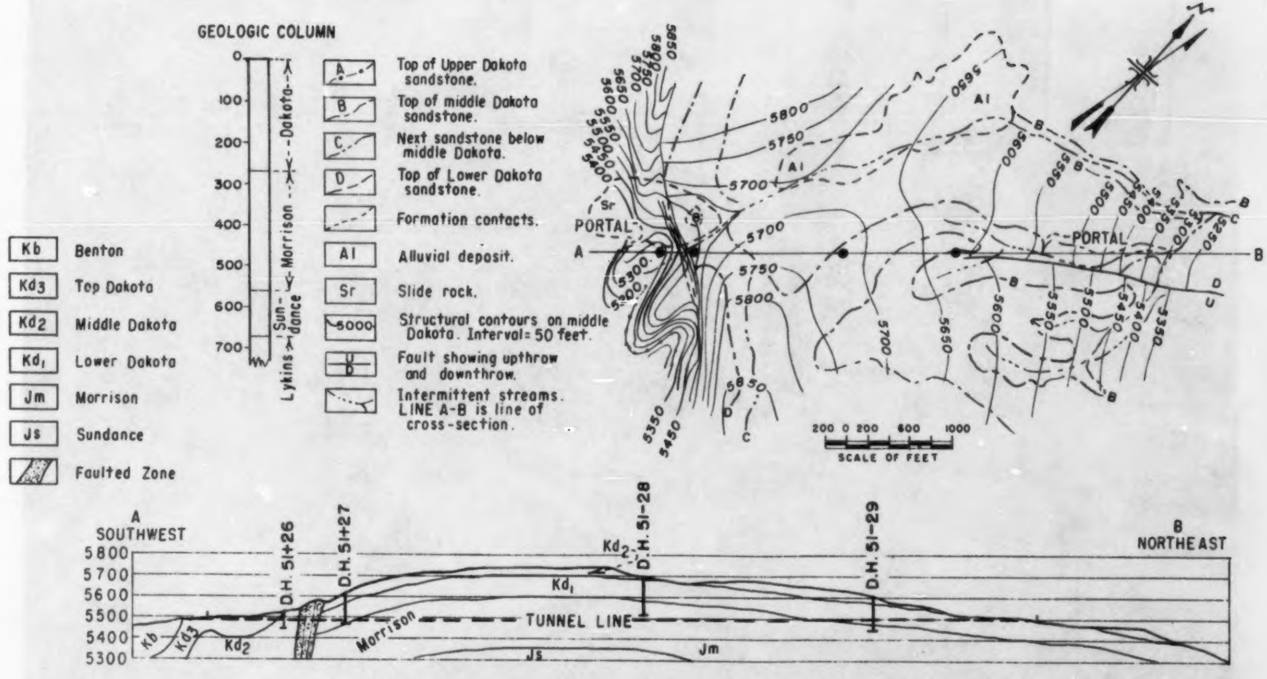


FIG. 5. Field Permeometer Test in Progress



RABBIT MOUNTAIN TUNNEL
GEOLOGIC MAP AND SECTION
Fig. 6

FIG. 7. Tunnel Support. 6" H-Beams on 1" Centers

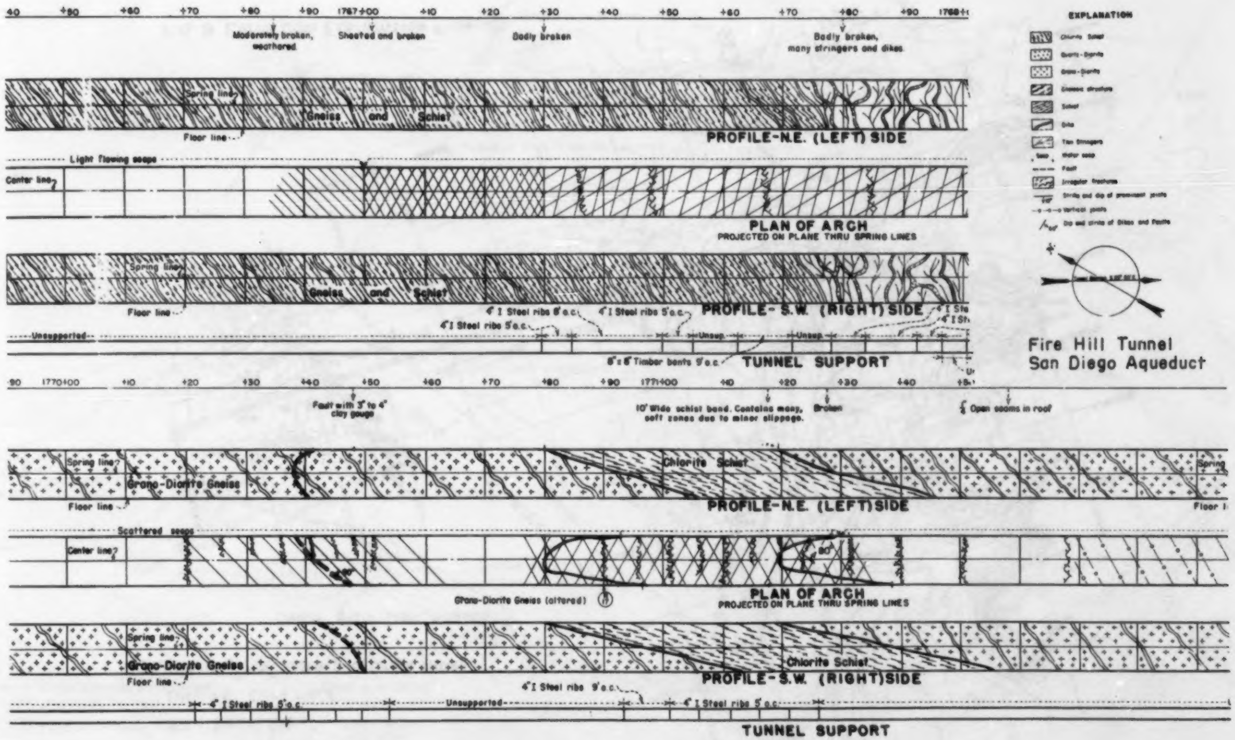


FIG. 8 Tunnel Log

TH - 6" Drive Hole
TP - Test Pit
DH - $1\frac{5}{8}$" Core Hole
OW - $2\frac{1}{2}$"-3" Core and Drive Holes

Cedar Bluff Dam, Kansas

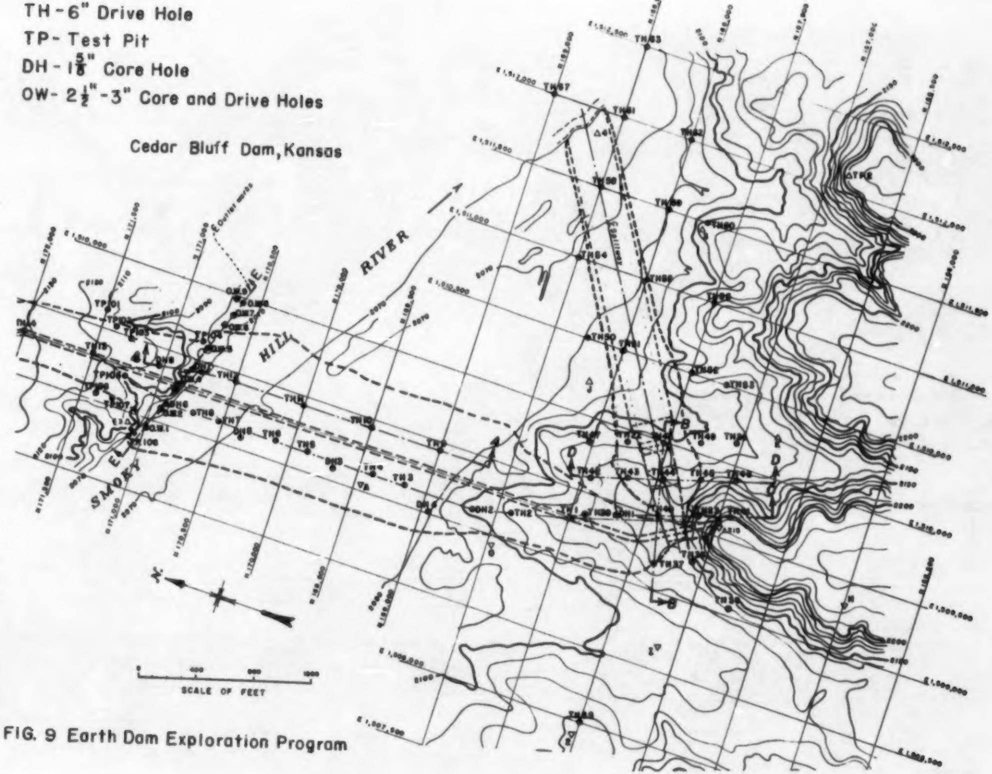


FIG. 9 Earth Dam Exploration Program

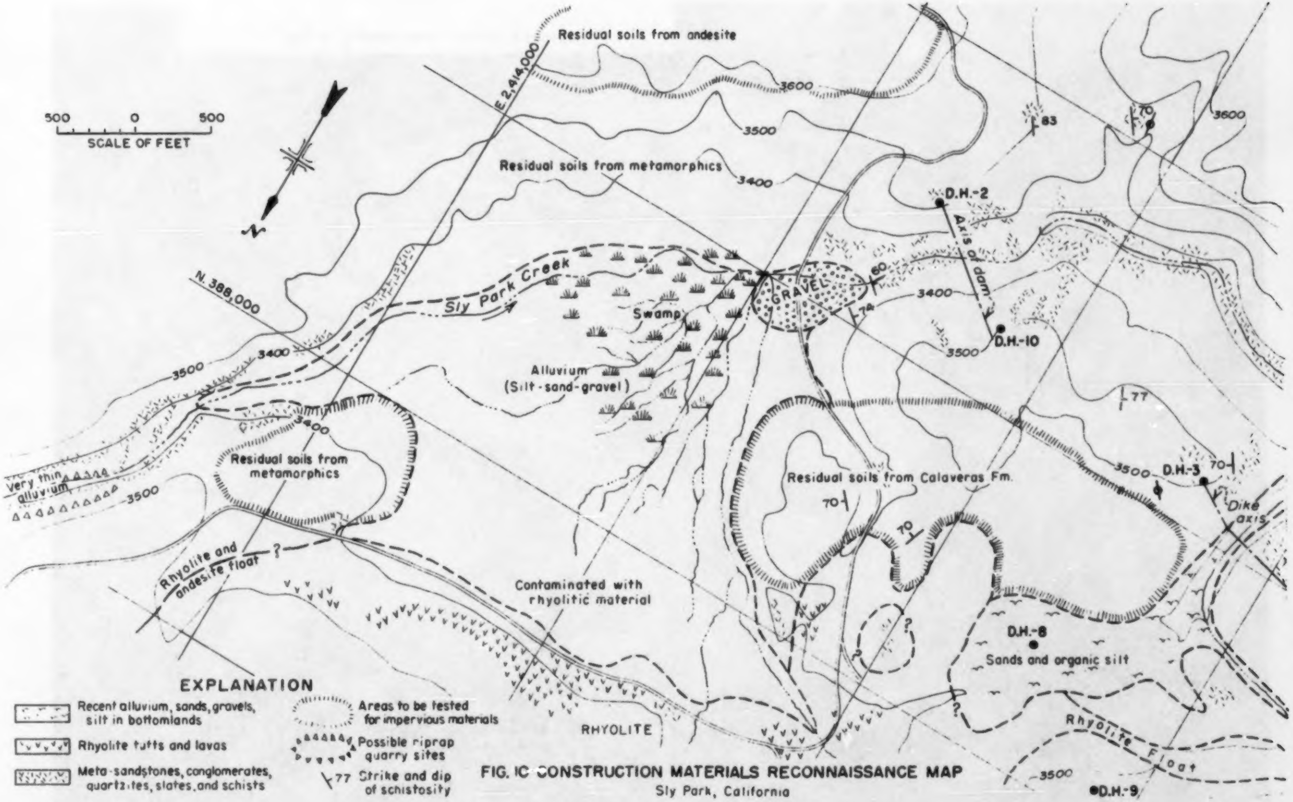
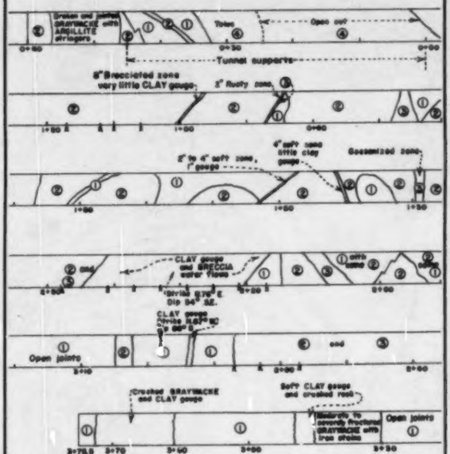


FIG. IC CONSTRUCTION MATERIALS RECONNAISSANCE MAP
Sly Park, California

FIG. 11 Exploratory Drift (Alaska)



EXPLANATION

① GRAYWACKE, relatively hard, very jointed some slickensides

② GRAYWACKE and ARGILLITE, decomposed and crushed, with many QUARTZ and CALCITE seams

③ CLAY GOUGE, very soft and iron stained with granular fragments of GRAYWACKE and ARGILLITE

④ OVERBURDEN material - TALUS

NOTE

Logged on right wall of approximately 5'x5' drift

X=Tunnel supports

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EKLUTNA PROJECT
EXPLORATORY DRIFT
GEOLOGIC LOG

FIG. 12.

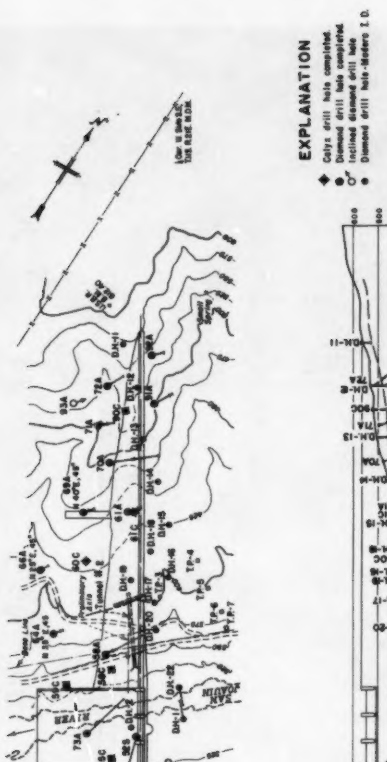

FIG. 13 Exploration Program for Concrete Dam (Friant Dam)